Epistemic and ontic interpretation of quantum mechanics:
Quantum information theory and Husserl’s phenomenology

T. BILBAN1*
1 Institute for Quantum Optics and Quantum Information, Boltzmannngasse 3, 1080 Vienna, Austria

Abstract: Since the beginning of quantum mechanical description there have been two approaches to its interpretation, the ontic and the epistemic approach. Up to today the approaches have remained unconnected, which is one of the main reasons for the lack of a common, complete interpretation of quantum mechanics. A possibility for exceeding this ontic/epistemic opposition can be offered by quantum information theory, which is essentially based on the epistemic approach, however when connected with Husserl’s phenomenology also offers a basis for an epistemic-ontic interpretation. In Zeilinger-Brukner’s quantum information theory, Kant’s understanding of the relationship between the phenomenon and the “thing-in-itself” has been used as a model for understanding of the relationship between information and the observed. If it is replaced by Husserl’s understanding of the relationship between the two, information and the observed can be understood as causally connected – information represents the direct answer to the question about the observed, while the basis for this information is the observed itself. This kind of approach offers the firm answer how to exceed solipsism and gain the common objectivity of quantum mechanical description, without introducing any further realism or loosing any explanatory power of quantum information theory: furthermore, the relationship between the observer, the observed and the observation can be now more thoroughly understood.

Introduction

The opposite between Einstein’s and Bohr’s approach towards quantum mechanics has been often described as the opposite between an epistemic and an ontic approach. Bohr’s approach has emphasized the epistemic
Quantum mechanics and phenomenology

point of view, otherwise overlooked in physics, while Einstein saw the classical point of view, labeled as scientific realism and apriori excluding the role of the observer, as the only appropriate stand point for physics. The lack of insight that they are approaching the problem from two different philosophical stand points, rather than understanding the same phenomena in the same context in different ways could be one of the main reasons for the lack of connection of their views: “Both Einstein and Bohr did not clearly realize that they addressed different concepts of reality, since they never made their basic viewpoints explicit. Both Bohr’s operationalistic and Einstein’s ontological concept of reality have their proper places in the study of matter. Both are legitimate and even necessary, but they must not be confused with each other.” [1]

On the one hand Bohr’s approach had the advantage of originating directly from the experiments and their most direct interpretation, without considering traditional notions about real and existing, and thus became the basis for physical interpretations of quantum mechanics. On the other hand more or less all ontic approaches (e.g. many worlds, hidden variables) originated from the opposition to the epistemic interpretations (most often gathered under the name Copenhagen interpretation) and not from its continuation or complementarity. For example the description of the hidden variable theory and its contribution to understanding of quantum reality in Bohm’s and Hiley’s book An Ontological Interpretation of Quantum Theory emphasizes the lack of ontology in the Copenhagen interpretation. However, they do not try to supplement it, but offer another, ontic instead of epistemic, interpretation: “Or to put it in more philosophical terms, it may be said that quantum theory is primarily directed towards epistemology which is the study that focuses on the question of how we obtain our knowledge […], it does not give what can be called an ontology for a quantum system. Ontology is concerned primarily with that which is and only secondarily with how we obtain our knowledge about this.” [2]

Both approaches stay unconnected within (more or less) all current interpretations, although their difference does not mean they are opposing each other, on the contrary – a complete interpretation should certainly consider both of them. According to Atmanspacher and Primas: “Drawing the distinction between epistemic and ontic descriptions does not imply, though, that the two categories are unrelated to each other. On the contrary, the crucial point is about the relationship between the two frameworks rather than the selection of one at the expense of the other.” [1]

An interesting possibility for exceeding this everlasting opposition can be offered by the quantum information theory. Quantum information theory is essentially based on the epistemic approach, but at the same time,
because of its connection with philosophical tradition, offers a possibility for a connection with Husserl’s phenomenological approach and therewith a possible basis for an epistemic-ontic interpretation of quantum mechanics.

**Epistemic interpretation of quantum mechanics – quantum information theory**

Quantum information theory is essentially connected with Bohr’s epistemic approach towards physical phenomena, which can be seen in the frequency of citations of the following reported to be Bohr’s quotation: “There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature.” [3] Quantum information theory is thus based on the hypothesis that “quantum physics is only indirectly a science of reality but more immediately a science of knowledge.” [4]

An important connection between the Copenhagen interpretation and its original proponents on the one side and quantum information theory on the other side is certainly Carl Friedrich von Weizsäcker’s philosophically-physical interpretation of quantum mechanics. Weizsäcker places the information as a fundamental concept of contemporary science, and thus Ur, an atom of information [5], as the basic element of the system. This principle is then used as the basis of quantum information theory. “So, what is the message of the quantum? I suggest we look at the situation from a new angle. We have learned in the history of physics that it is important not to make distinctions that have no basis […] I suggest that in a similar way, the distinction between reality and our knowledge of reality, between reality and information cannot be made.” [6] Our description of nature thus deeply depends on the characteristics of the system of information. The fundamental principle of quantum information theory is, according to Zeilinger, that an elementary system has the information carrying capacity of at most one bit [7] and on this basis fundamental quantum phenomena, such as Heisenberg’s uncertainty principle [8] or entanglement [9] are explained.

This merely epistemic approach of quantum information theory also makes its explanation of the collapse of wave function possible: “This, sometimes called reduction of the wave packet or collapse of the wave function, can only be seen as a measurement paradox if one views this change of the quantum state as a real physical process. In the extreme case it is often even related to an instant collapse of some physical wave in
space. There is never a paradox if we realize that the wave function is just
an encoded mathematical representation of our knowledge of the system.
When the state of a quantum system has a non-zero value at some position
in space at some particular time, it does not mean that the system is physi-
cally present at that point, but only that our knowledge (or lack of knowl-
edge) of the system allows the particle the possibility of being present at
that point at that instant. What can be more natural than to change the
representation of our knowledge if we gain new knowledge from a mea-
surement performed on the system? When a measurement is performed,
our knowledge of the system changes, and therefore its representation, the
quantum state, also changes. In agreement with the new knowledge, it in-
stantaneously changes all its components, even those which describe our
knowledge in the regions of space quite distant from the site of the mea-
surement.” [10]

But as the approach of the quantum information theory is fundamen-
tally epistemic, the objectivity of the information cannot be taken as self-
evident on the basis of the common, from us independently existing outer
world, as is the fact in classical physics. The coincidence in quantum-
mechanical processes, completely independent from the observer, and ex-
remely high accuracy and objectivity of the estimation of probabilities,
indicate that it is not (only) the closed system of the (subjective) observer’s
information we are talking about, but that they rely on the, from us inde-
pendent, reality. Nevertheless, the objectivity of the quantum world can
be taken into account only on the basis of certain invariants, and of the
inter-subjective agreement about the gained information and their mean-
ing. On this basis it is possible to exceed the solipsism and to conclude that
a system of information, independent from us, forms the objective reality,
so that the outer world (in that sense) exists. “Andererseits kann es sein,
dass diese Übereinstimmung zwischen verschiedenen Beobachtungen be-
deutet, dass eine Welt existiert. Eine Welt, die so beschaffen ist, dass die
Information, die wir besitzen – und wir besitzen nicht mehr –, offenbar in
gewisser Weise auch unabhängig vom Beobachter besteht.” [8] But still,
since this approach is merely epistemic, there is no direct connection be-
tween the information and “that something this information is about”. On
this basis we can speak about an objective inter-subjective world of informa-
tion, however we cannot speak about an objective outer world that this
information is about. If information is all that exist, then there is nothing
this information is about. And on this point the supplementation of this
complex epistemic approach by a philosophical-ontic interpretation seems
fruitful for further and wider investigation.
Connections with philosophical systems

Immanuel Kant

The relationship between the observer, the observation and the observed has not been seen as particularly important in classical physics, where objects of physical observation and their independence from the observer have been taken for granted. On the contrary, this question has always been seen as crucial in philosophy and has very often been built into more complex philosophical systems. Therefore, one could say that quantum mechanics has not really opened a new problem, but has shed light on an old philosophical problem from a physical side. This opens a possibility for more complex processing of the problem, but since all traditional philosophical systems deal with these questions by only considering classical physics, one has to be very careful while transmitting certain philosophical approaches to the quantum field.

An important, complex and systematic philosophical treatment of the question of relationship between the observer and the observed is represented in Kant’s Critique of Pure Reason [11]. As Kant’s philosophy had an important place in general education at the time these questions were recognized as important in physical field and as his systematic, mainly epistemic approach offered an interesting basis for further reasoning, some parts of his approach have become, more or less directly and complexly, involved in physical reasoning about this questions.

In Critique of Pure Reason Kant emphasizes that what we are observing are not “things-in-themselves”, but phenomena (“things-for-us”, the observation). For something to become an object of knowledge, it must be experienced, and experience is structured by our minds. Therefore causality, time and space are not the conditions of the experienced world, but are forms of our cognition (space and time are forms of perceiving and causality is a form of knowing). The relationship between “things-in-themselves” and phenomena is therefore not causal. “Also ist es nur die Form der sinnlichen Anschauung, dadurch wir a priori Dinge anschauen können, wodurch wir aber auch die Objekte nur erkennen, wie sie uns (unsern Sinn) erscheinen können, nicht wie sie an sich sein mögen.” [12]

Kant’s method, his distinction between phenomena and “things-in-itself”, has offered an interesting basis for consideration of the relationship between the observer, the observation, and the observed. However, as Grete Herman already emphasized in the dialog with Heisenberg and Weizsäcker, in Kant’s philosophy the place of the physical object is solely on the side of phenomena, therefore the difference between the-thing-in-itself and the phenomena, as developed by Kant, cannot be transmitted to
the relationship between the physical object and the information about it, if one stays in accordance with Kant’s philosophical system: “Sie müssen deutlich unterscheiden zwischen dem Ding an sich und dem physikalischen Gegenstand. Das Ding an sich tritt nach Kant in der Erscheinung überhaupt nicht auf, auch nicht indirekt. Dieser Begriff hat in der Naturwissenschaft und in der ganzen theoretischen Philosophie nur die Funktion, dasjenige zu bezeichnen, worüber man schlechterdings nichts wissen kann. [...] Wenn Sie im Sinne der klassischen Physik vom Radium B-Atom “an sich” sprechen, so meinen Sie damit also eher das, was Kant einen Gegenstand oder ein Objekt nennt. Objekte sind Teile der Welt der Erscheinung: Stühle und Tische, Sterne und Atome.” [13]

Therefore, although Kant’s approach is mainly epistemic, his philosophical system as such is incompatible with quantum physics or at least with its epistemic interpretations, since ontic interpretations are much closer to classical views on the relationship between the observer and the observed. Nevertheless, his method – his refined relationship between the phenomenon and “thing-in-itself” – is compatible with (orthodox) epistemic interpretations of quantum mechanics. His definition of the relationship between the two (although transmitted from the relationship between “thing-in-itself”: phenomenon to the relationship observed: information) has been thus, with more or less awareness of its source and more or less completely, frequently integrated into the epistemic quantum interpretations. This can be seen in quantum information theory and its interpretation of the relationship between the information and “that something this information is about”.

However, the more than 200 years old Kant’s philosophical system has been, since its formation, frequently re-considered within the field of philosophy. The lack of permeability between the “thing-in-itself” and the phenomena, which can not be causally connected, even though some kind of connection between the two exists, has been recognized as one of the most problematic parts of his system, [14] even by Kant himself: “…though we cannot know these objects as things in themselves, we must yet be in a position at least to think them as things in themselves; otherwise we should be landed in the absurd conclusion that there can be appearance without anything that appears.” [11]

Because the main features of the relationship between the information and “that-something-this-information-is-about” in quantum information theory are quite similar to Kant’s definition of relationship between the phenomena and the “thing-in-itself”, the problems that this kind of approach is facing are similar as well. Information is sensible only as long it
is information about something, but if information is everything it is, what is the information about?

Edmund Husserl

In the philosophical field an answer has been provided by Husserl’s approach towards the observer and the observed within his phenomenology. His approach is still mainly epistemic, but maintains the permeability between the “thing-in-itself” and the phenomenon. Despite later criticisms and additions to his system, his construct of phenomenon being essentially related to both: to the observer (and his way of observing) and to the observed itself, has remained intact. For Husserl phenomenon means: the object as has been given to me by itself, but essentially to me, in the way to have a meaning (exactly) to me. Husserl’s phenomenon still depends on the observer’s cognition but at the same time also on the observed. The connection between the two is causational – “Es ist also ein prinzipieller Irrtum zu meinen, es komme die Wahrnehmung (und ihrer Weise jede andersartige Dinganschaug) an das Ding selbst nicht heran. Dieses sei an sich und in seinem Ansich-sein uns nicht gegeben. Es gehöre zu jedem Seiendem die prinzipielle Möglichkeit, es, als was es ist, schlicht anzuschauen und speziell es Wahrzunehmen in einer adäquaten, das leibhaftige Selbst ohne jede Vermittlung durch “Erscheinungen” gebenden Wahrnehmung.” [15]

As such Husserl’s philosophical approach towards the relationship between the phenomenon and the “thing-in-itself” (again as with Kant it is not the whole philosophical system that is transmitted, but solely his approach towards this relationship) seems as an interesting possibility for the substitution of quantum information theory’s description of the relationship between the information and “that something information is about” within quantum reality.

The connection between the quantum information theory and Husserl’s phenomenological approach towards the relationship between the observation and the observed gives the following result: Information and “that something this information is about” within the quantum information theory are causally connected – the information represents the direct answer to the question about the observed (information as the “eigen value” in the case of the description of the measurement in Hilbert space), the basis for this information is, however, the observed itself (“quantum system” in the case of the description of the measurement inside Hilbert space). This connection makes the information meaningful (it is information about something, for example value of the position or of the polarization of
the (observed) photon) and supplements the merely epistemic quantum-information approach with an ontic approach, without introducing quantum realism.

**Epistemic and ontic interpretation of quantum mechanics – further derivations**

Based on the presented possibility of ontic-epistemic interpretations of quantum mechanics some further philosophical-physical issues can be detailed. Beside the relationship between the observation and the observed, also the relationship between the two and the observer has been frequently considered in philosophy, but has not been particularly important in classical physics, while it has been recognized as relevant in quantum physics. The presented ontic-epistemic approach offers following considerations of the relationship between the information and the “that something this information is about” (the observed) on the one side and the observer on the other side – they are both in two ways connected to the observer:

1. To the observer as observer per se, as to the one for whom they have a meaning. There the observer and his way of comprehension can be seen as the answer to the question “Why information”.

2. To the observer as to the part of an environment, as to the one, who, by trying to get any information, already (necessary) has an influence on the observed and on the information about it.

The first connection is merely epistemic. The information has a meaning as information only as long it is information for someone. Most probably the preconditions of our comprehension are those that determine information as the form, in which everything we comprehend is given. (If our cognition is not taken as something pre-given but as something that has evolved itself as an efficient process for survival in our environment, the relationship is ontic-epistemic already at this point. The reason for our cognition being such that it grasps the world in the form of information is that this is one of the (most) suitable ways to survive in this world. This approach offers also a possible answer to the question of why classical physics seems more intuitive as quantum physics. The answer is: because the comprehension of classical systems is far more crucial for survival.) However, the second connection is merely ontic. Since information is always information about something, in the case of the measurement not only our information about the observed system is changed, but the observed system as entangled with the measurement apparatus (and thus
with our classical system) as well. This process has been described by decoherence.

Both connections emphasize the transition from quantum to classical. Decoherence of the observed quantum system and thus its connection with our classical environment makes it possible to describe it in our classical language and to transmit some characteristics of our classical system to it, and can be thus seen as the basis for the ontic description of the transition from quantum to classical description. However, this transition has to be described from the epistemic point of view as well.

Concepts that we know from our every-day experience are classical concepts, since we know they rely on complex systems, but we do not have any basis for connecting them with coherent quantum systems. Any direct observation would cause decoherence and would thus a-priori disable the observation of the coherent quantum system. An abstract mathematical description of the coherent quantum system is a meaningful operationalistic description of the system we are not directly connected to (which is not directly observed). On the other hand, any interpretation of this description based on the usage of classical concepts has no basis. It is meaningless to speak about the “real existence” of the wave function, or to describe coherent quantum system within the concepts of time and space, since these are classical concepts, based on our everyday experiences in the world of complex decohered systems.

However, another important consideration of the transition from quantum to classical is based on the logical postulate that to describe something it is necessary to be outside the described set. This postulate operationally explains the cut between quantum and classical in the process of measurement and is thus (more or less) identical to Heisenberg’s consideration of this problem known as “Heisenberg cut” [16]. “There arises the necessity to draw a clear dividing line in the description of atomic processes, between the measuring apparatus of the observer which is described in classical concepts, and the object under observation, whose behaviour is represented by a wave function.” [17] “This cut can be shifted arbitrarily far in the direction of the observer in the region that can otherwise be described according to the laws of classical physics, […] but […] the cut cannot be shifted arbitrarily in the direction of the atomic system” [18]. This cut is a necessary condition for the possibility of empirical knowledge and is as such operationalistic, but not arbitrary. On the one hand the choice depends on the nature of experiment, and on the other hand, since quantum description is universal, while classical physics can describe only complex classical systems, the cut cannot be shifted arbitrary in the direction of the atomic system.
Connection with the experiment: Delayed choice entanglement swapping

In the following chapter the above represented interpretation is applied to an experiment in order to offer a clearer representation. The experiment – “Delayed choice entanglement swapping experiment” has been chosen as a recent experiment that deals with the foundational questions and emphasizes some essential characteristics of quantum mechanics, which are often seen as peculiar.

The experiment is based on the swapping of entanglement within two systems of entangled photons: two observers (Alice and Bob) independently prepare two entangled particles. They test one particle of each pair (1 and 4) along an arbitrarily chosen direction and send the other particle (2 and 3) to a third observer, Victor. At a later time (optical delay), Victor decides either to entangle particles 2 and 3 or not and then test them as well. According to his choice of test and to his results, Alice and Bob can sort into subsets the samples that they have already tested, and in the case, when particles 2 and 3 has been entangled, the the data of particles 1 and 4 suggest that they have been entangled as well, although they have never communicated in the past, not even indirectly via other particles. [19, 20, 21]

But the situation seems less peculiar if our understanding originates from the clear distinction between the observed systems and the information about it. Individual values of measurements are our information about the observed, the entanglement witness (the data on the basis of which we conclude that two photons are entangled – see the figure below [21]) represents the relationships between the information. On the one hand information has a meaning only as long it is information about the observed systems – in our case about one of the observed photons (or of the system of two entangled photons). On the other hand our investigation of possible entanglement is not based on direct observation and interpretation of the whole observed system as it was the case in classical physics, but on the measurement, which gives us information about the chosen property of the observed, polarization of the photons in our case, and afterwards on the interpretation of this information (entanglement witness is not information about the relationship between two observed photons, but is the relationship between the information about the photons). Therefore it is meaningless to speak about a causal relationship between the entanglement of the photons 2 and 3 and the nature of relationship between the photons 1 and 4, since (at the last step) it is information about the observed system we are interpreting with and not the observed photons by itself.
This is clearly represented in figure 1: without the left column that connects information with “that-something this information is about”, the interpretation of the information would lose its content. Nevertheless, it is the interpretation of the information within the four columns on the right that gives us the basis to speak about entanglement between photons that have never communicated with each other.

<table>
<thead>
<tr>
<th>Photon pairs</th>
<th>Measurement $i$</th>
<th></th>
<th>Measurement $ii$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>State fidelity</td>
<td>Entanglement</td>
<td>State fidelity</td>
<td>Entanglement</td>
</tr>
<tr>
<td>2 and 3</td>
<td>0.645 ± 0.031</td>
<td>−0.145 ± 0.031</td>
<td>0.379 ± 0.026</td>
<td>0.120 ± 0.026</td>
</tr>
<tr>
<td>1 and 4</td>
<td>0.681 ± 0.034</td>
<td>−0.181 ± 0.034</td>
<td>0.421 ± 0.029</td>
<td>0.078 ± 0.029</td>
</tr>
<tr>
<td>1 and 2</td>
<td>0.301 ± 0.039</td>
<td>0.199 ± 0.039</td>
<td>0.908 ± 0.016</td>
<td>−0.408 ± 0.016</td>
</tr>
<tr>
<td>3 and 4</td>
<td>0.274 ± 0.039</td>
<td>0.226 ± 0.039</td>
<td>0.864 ± 0.019</td>
<td>−0.364 ± 0.019</td>
</tr>
</tbody>
</table>

Table 1: Delayed choice entanglement swapping experiments results [21].

Conclusions

A reconsideration of a merely epistemic quantum information theory within continental philosophy offers a possibility for an ontic supplementation. If we follow Husserl’s understanding of the relationship between phenomena and “thing-in-itself” when considering the relationship between information and the observed in quantum information theory, information and the observed can be seen as causally connected and information can be understood as information about the observed. This approach thus offers the firm answer how to exceed solipsism and gain common objectivity of quantum mechanical description, without introducing further realism, since everything that we can say about the observed, beside the answer given by the information about it, is that it exists, and it is senseless to speak about any pre-given properties. Thus we avoid a radical epistemic point of view, where everything that exists is solely our knowledge. Thereby we avoid facing the Descartian way of reduction in which there is no point where someone could stop and recognise something as existing (not even the observer as the one having that knowledge) and thus as the basis for any hypothesis about reality. But at the same instance we also avoid wasteful scientific realism, bringing huge amount of new elements into the description (either variables, worlds or something else), that can be seen as an interesting alternative form physical operationalistic point of view, but certainly as problematic from the philosophi-
cal point of view, since a huge amount of unintuitive, not evidence based elements have been brought into picture on one side, to avoid unintuitive-ness on the other side. This small, but fundamental change in philosophical understanding of the ontic status of information and its basis solves important philosophical problems regarding the relationship between the observer, the observation and the observed (as are “what is the information about”, “what exists”, “why this information”, “how to gain objectivity”, etc.) without loosing any explanatory power of quantum information theory. This kind of picture is much more consistent from the philosophical point of view and thus offers a more firm basis for further consideration, therefore some fundamental principles of quantum information theory can now be re-thought within this philosophical context. The prospects of this philosophical approach are thus the reconsideration and supplementary support of the fundamental elements of the theory, as are: the character of information and the principle that an elementary system has the information carrying capacity of at most one bit.

**Acknowledgement**

This work was supported by a grant from the John Templeton Foundation. I would like to thank Markus Aspelmeyer, Caslav Brukner, Johannes Kofler and Anton Zeilinger for inspiring discussions and helpful comments.

**References**


